Aerodynamic Design Optimization of a Transonic Strut-Braced-Wing Regional Aircraft

Timothy Chau and David W. Zingg
University of Toronto Institute for Aerospace Studies

Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, October 7, 2021

Introduction

Motivation

- Growing concerns surrounding the environmental sustainability of commercial aviation has motivated the need for greener aircraft
  - IATA: Reduce fuel burn and CO_2 emissions by 50% by 2050, relative to 2005 levels
- Step changes in environmental impact will require major advances from various areas:
  - Advanced aerodynamic technologies
  - Advanced structures and materials
  - Advanced propulsion technologies
  - Alternative fuels
- One major contribution is anticipated to come from unconventional aircraft configurations that have the potential to provide major savings in fuel burn, relative to the conventional tube and wing design

Unconventional Aircraft Configurations

Image credits: *NASA/Boeing* (BWB), *Aurora Flight Sciences* (D8), *Lockheed Martin* (Box Wing), *Boeing* (Truss-Braced Wing)

Strut- and Truss-Braced Wings

Advantages

- Significantly lower induced drag due to larger wing span
- Higher structural efficiency due to truss topology
  - Supports higher wing bending loads
  - Enables thinner wings
  - Lowers structural weight

Aerodynamic Design Challenges

- Shock formation in truss region due to flow acceleration in small enclosed space(s)
- Flow interference + skin friction drag penalties from strut members

Aerodynamic design challenges must be addressed at Mach 0.78-0.80 to obtain a **credible estimate for the fuel burn advantage** of the configuration.

*Strut-braced wing = main strut only, truss-braced wing = main strut + jury strut(s)

Image credits: *Boeing*

Aerodynamic Shape Optimization

- Aerodynamic shape optimization automates the design process through specified objective functions, design variables and constraints, eliminating the need for extensive *a priori* design experience

- Aerodynamic shape optimization based on the Reynolds-averaged Navier-Stokes (RANS) equations:
  - Captures shock formation, boundary-layer separation, and nonlinear interference effects
  - Accurately captures and enables tradeoffs between induced drag, viscous drag, and wave drag

$\boxed{M = 0.78,\ Re = 20 \times 10^6}$

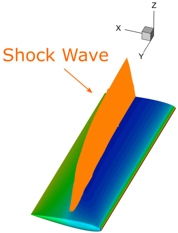
Initial

$\alpha = 1.00°$

$L/D = 8.7$

$C_L = 0.09$

$C_D = 0.0107$



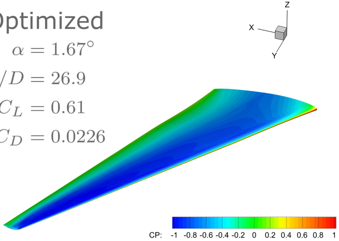
Optimized

$\alpha = 1.67°$

$L/D = 26.9$

$C_L = 0.61$

$C_D = 0.0226$



Questions to Address

1. Can we mitigate shock wave formation within the wing-strut junction at high transonic Mach numbers using high-fidelity aerodynamic shape optimization?

2. How do we design an optimal strut-braced-wing transport aircraft when accounting for tradeoffs between induced drag, viscous drag, and wave drag?

3. How much of a fuel burn savings can we expect over the conventional tube-and-wing for the strut-braced-wing configuration in the regional jet class with current technology levels?

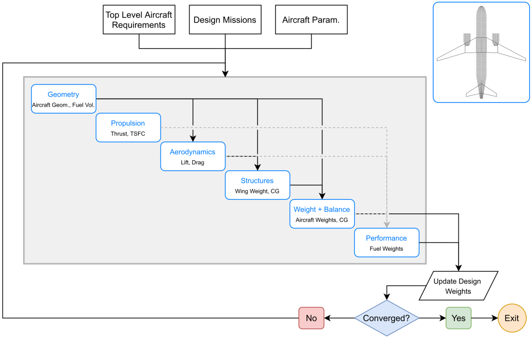
This work will attempt to answer these questions through the application of **Aerodynamic Shape Optimization based on the Reynolds-averaged Navier-Stokes (RANS) equations**.

A conventional tube-and-wing regional jet will also be optimized to serve as a performance baseline.

Computational Design Tools

Faber: Conceptual Design Environment for Transport Aircraft

- Multidisciplinary design optimization (MDO) through low-order modeling
  - Aircraft system sizing
  - Top level aircraft requirements
  - Mission performance
- For unconventional wings:
  - Finite beam model for wing weight estimation
  - Global buckling detection
- Optimizes/sizes:
  - Wing planform
  - Tail planforms
  - Propulsion system
  - Operating conditions



Sizing routine called by optimizer.

Chau and Zingg, *Journal of Aircraft*, 2021. doi: 10.2514/1.C036389

Jetstream: High-Fidelity Aerodynamic Shape Optimization

Mesh Parameterization and Deformation[1], Geometry Control[2]

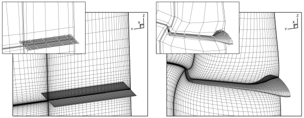
- B-spline volume parameterization
- Linear elasticity model for deforming B-spline volumes
- Axial and free-form deformation method

Structured Multiblock Flow Solver[3]

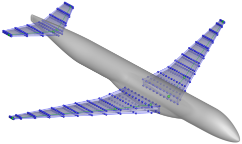
- Reynolds-averaged Navier-Stokes (RANS) equations fully-coupled with Spalart-Allmaras (SA) turbulence model; includes QCR2000
- Parallel implicit Newton-Krylov-Schur method

Optimization and Gradient Evaluation[4]

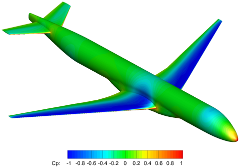
- SNOPT for gradient-based optimization
- Large-scale linear and nonlinear constrained problems
- Discrete adjoint method, analytical, complex step



Mesh parameterization and deformation



Geometry control system



Optimized aerodynamic design

[1] Hicken and Zingg, *AIAA Journal*, 2010. doi: 10.2514/1.44033
[2] Gagnon, and Zingg, *AIAA Journal*, 2015. doi: 10.2514/1.J053575
[3] Osusky, M. and Zingg, *AIAA Journal*, 2013. doi: 10.2514/1.J052487
[4] Osusky, L. et al., *AIAA Journal*, 2015. doi: 10.2514/1.J053457

Conceptual Design

Design Requirements: Missions and Sizing

Reference aircraft: **Embraer E190-E2**

- Maximum payload = 30,200 lb
- Design payload = 104 passengers
- Design range = 3,100 nmi
- Nominal range = 500 nmi
- Mach 0.78
- W/S = 110.2 lb/ft^2, T/W = 0.336
- Pratt & Whitney PW1919G engines

Assume current technology levels for strut-braced wing

- Composite wing structures
- No natural laminar flow wings
- No advanced flow control
- No new engine technology

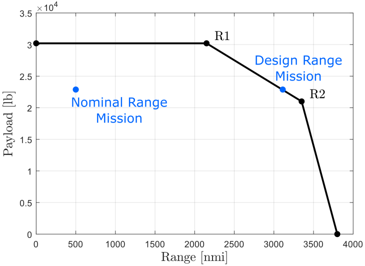


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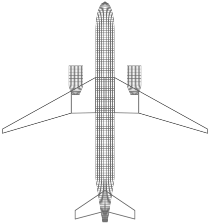
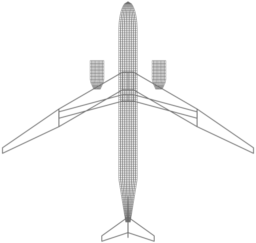
Image credits: *Embraer*

Results: Conceptual-Level MDO



CTW100



SBW100

Parameter	CTW100	SBW100	Δ
Geometry			
Mean aerodynamic chord [ft]	12.82	8.35	–
Span [ft]	110.6	136.0	–
Aspect ratio [–]	10.84	17.32	+59.8%
Wing wetted area [ft^2]	1,914	2,603	+36.0%
Reference area [ft^2]	1,129	1,068	–
Weights			
MTOW [lb]	124,290	117,710	−5.3%
MZFW [lb]	102,870	98,790	–
OEW [lb]	72,670	68,590	−5.6%
MFW [lb]	30,130	26,200	−13.0%
Maximum payload	30,200	30,200	–
Design payload (104 PAX)	22,880	22,880	–
Propulsion			
Maximum TO thrust (per engine) [lb]	20,860	19,780	–
Cruise TSFC [lb/lb/hr]	0.5872	0.5900	+0.5%
Aerodynamics			
Mach number [–]	0.78	0.78	–
Initial cruise altitude [ft]	37,000	44,670	–
Reynolds number [million]	22.04	9.92	–
Cruise L/D [–]	18.1	21.0	+16.0%
Cruise C_L [–]	0.468	0.682	–
Cruise lift [lb]	101,720	97,000	–
Cruise drag [lb]	5,620	4,610	–
Fuel			
Block fuel [lb]	5,160	4,720	−8.5%

[1] All operating conditions and cruise parameters are in reference to the start of cruise for the 500 nmi mission

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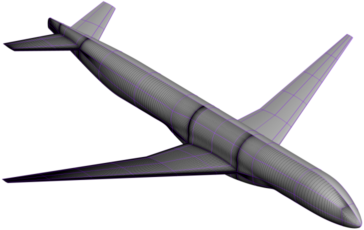
High-Fidelity Aerodynamic Shape Optimization

Geometry and Mesh

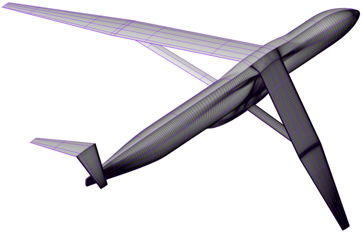
Grid	Num. of Nodes	Avg. Off-wall Spacing[1]	Average y^+
Conventional Tube-and-Wing			
L0	14.41×10^6	8.84×10^{-7}	0.53
L1	27.56×10^6	6.92×10^{-7}	0.41
L2	54.85×10^6	5.36×10^{-7}	0.31
Strut-Braced Wing			
L0	26.51×10^6	1.91×10^{-6}	0.57
L1	50.50×10^6	1.50×10^{-6}	0.43
L2	99.54×10^6	1.16×10^{-6}	0.33

[1] Off-wall spacings are in units of mean aerodynamic chord

- Based on Drag Prediction Workshop (DPW) gridding guidelines
- Optimize on *medium* mesh resolution, which is "representative of current engineering drag predictions"
- Richardson extrapolation performed post-opt. to estimate grid-converged C_L, C_D, and L/D



CTW100

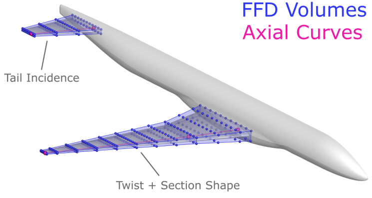


SBW100

Aerodynamic Shape Optimization Problem Definitions

Conventional Tube-and-Wing

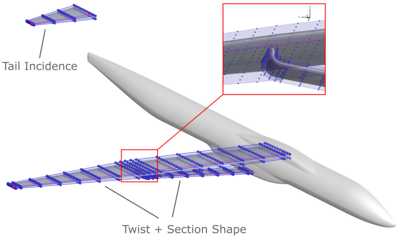
Objective	Minimize cruise drag
Design Variables (281)	Angle of attack (1)
	Twist (16)
	Section shape (264)
Nonlin. Constraints (13)	Constant lift (1)
	Zero pitching moment (1)
	Minimum wing volume (1)
	Minimum $(t/c)_{\max}$ (10)



CTW100

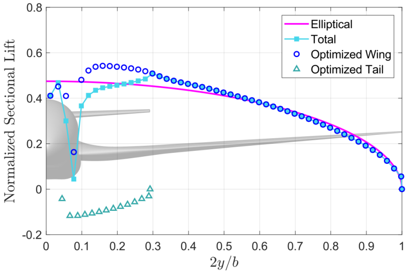
Strut-Braced Wing

Objective	Minimize cruise drag
Design Variables (946)	Angle of attack (1)
	Twist (43)
	Section shape (902)
Nonlin. Constraints (33)	Constant lift (1)
	Zero pitching moment (1)
	Minimum wing/strut volume (1)
	Minimum $(t/c)_{\max}$ (30)

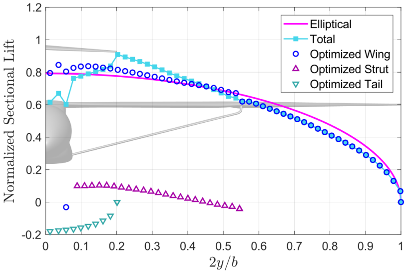


SBW100

Results: Single-Point Optimized Spanwise Lift Distributions



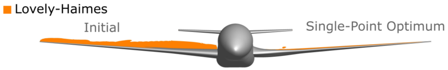
CTW100



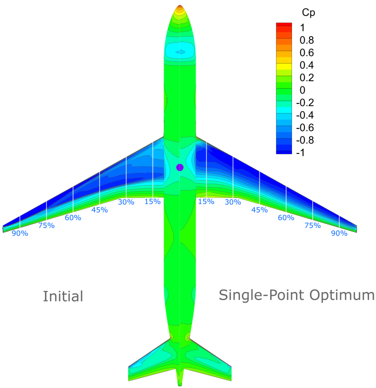
SBW100

- Elliptical in form but shifted inboard due to trim constraint, and to avoid high sectional C_L over outboard portion of wing
- Negative lift over strut is introduced to alleviate adverse flow effects within wing-strut junction; compensated by more lift over inboard portion of wing
- Strut produces some lift near root

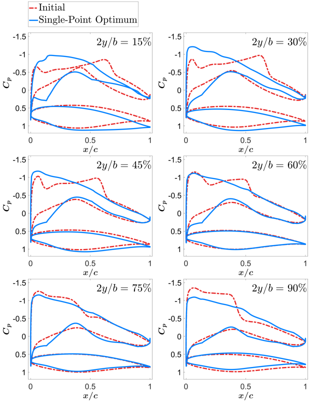
Results: Single-Point Optimized CTW100



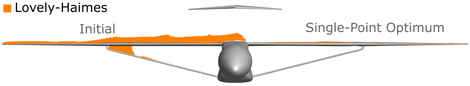
Shock surfaces



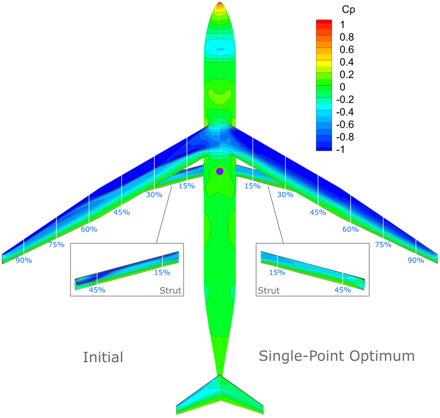
Surface pressure contours



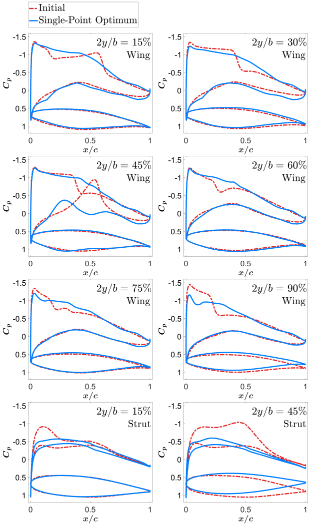
Pressure distributions



Shock surfaces

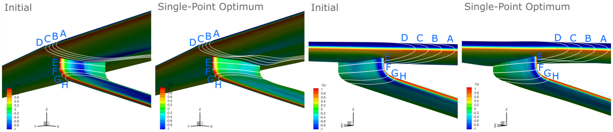


Surface pressure contours

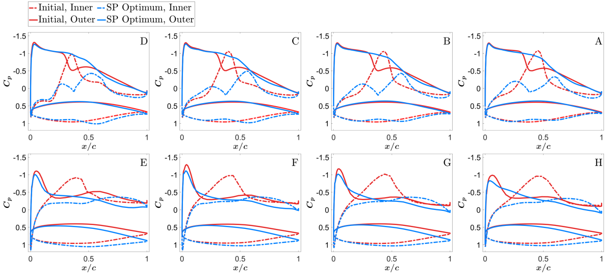


Pressure distributions

Results: Junction Design and Performance



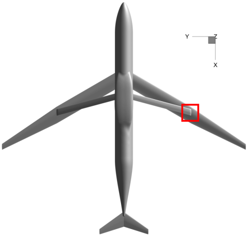
Inner (left) and outer (right) views of the wing-strut junction with surface pressure contours.

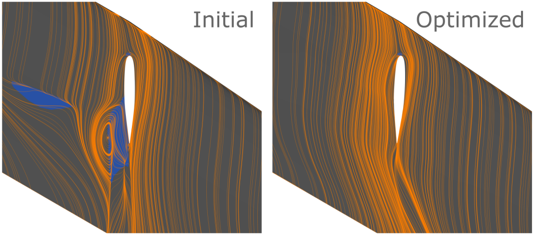


Airfoil profiles and pressure distributions over the wing and strut near the wing-strut junction.

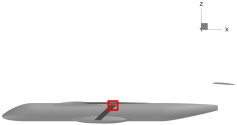
Novel airfoil shapes and an outwards force distribution over the strut helps alleviate the transonic channel effect and hence mitigates shock formation.

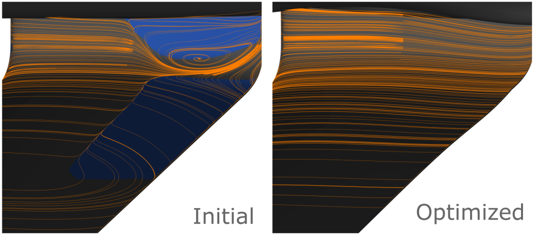
Results: Junction Streamlines and Separation Surfaces





A view of the lower wing surface.





A view of the inner strut surface.

Results: Single-Point Optimized Aircraft Performance

For block fuel, we reintroduce from the low-order models:

- Excrescence drag
- Drag for vertical tail, nacelles, and pylons
- Weight and propulsion
- Fuel from takeoff, climb, descent, and landing

Parameter	CTW100	SBW100	Δ
Wing, Fuselage, Horizontal Tail (High Fidelity)			
Cruise L/D [–]	22.33	24.46	+9.5%
Cruise C_L [–]	0.468	0.682	+45.6%
Cruise C_D [–]	0.0210	0.0279	+32.9%
Cruise lift [lb]	101,720	97,000	−4.6%
Cruise drag [lb]	4,555	3,966	−12.9%
Full Aircraft (Low + High Fidelity)			
Cruise L/D [–]	18.96	21.40	+12.9%
Cruise C_L [–]	0.468	0.682	+45.6%
Cruise C_D [–]	0.0247	0.0318	+28.9%
Cruise lift [lb]	101,720	97,000	−4.6%
Cruise drag [lb]	5,365	4,532	−15.5%
Block fuel [lb]	5,028	4,643	−7.6%

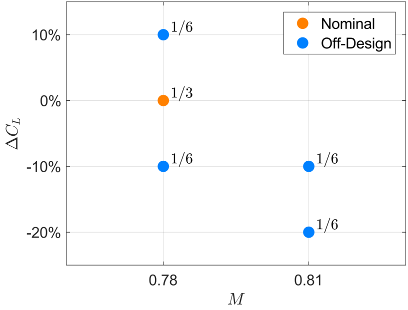
[1] Performance parameters are for the 500 nmi nominal mission.

Multipoint Optimization Problem

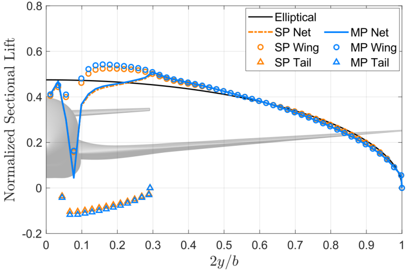
Can the low drag of the strut-braced-wing regional jet be maintained over a range of suitable cruise conditions? How does this impact block fuel performance?

$$\text{minimize} \quad \mathcal{J} = \sum_{i=1}^{N} \mathcal{D}(M_i, C_{L_i}) C_D(M_i, C_{L_i})$$

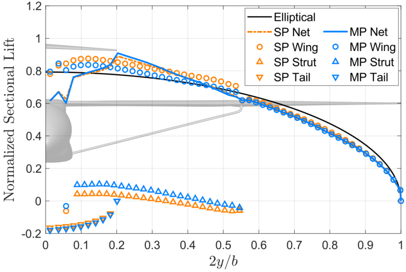
- Includes $\pm 10\% C_L$ conditions from the nominal design point
- Includes high speed design points at Mach 0.81
- Design weights selected to place $2\times$ priority on the nominal design point



Results: Multipoint Optimized Spanwise Lift Distributions



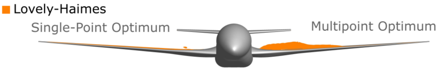
CTW100



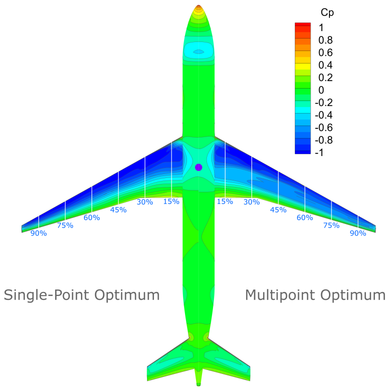
SBW100

- Negative lift on horizontal tail increased to compensate for higher inboard wing (and strut) loading
- Higher strut loading enables reduced wing loading to decrease wing C_L

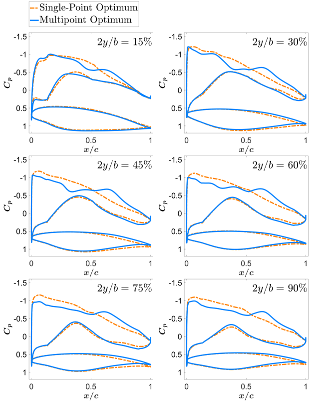
Results: Multipoint Optimized CTW100



Shock surfaces

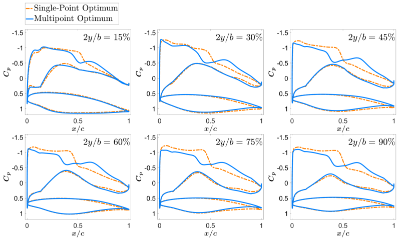


Surface pressure contours

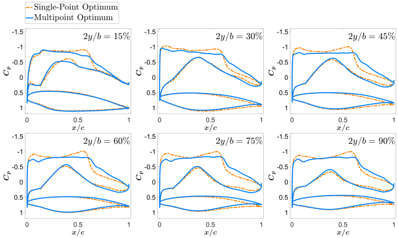


Pressure distributions

Results: CTW100 - Off-Design Performance



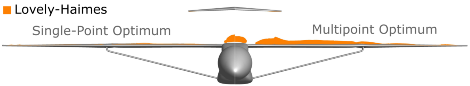
Design point 2: $M = 0.78$ and $C_L = 0.515$ (+10% nominal)



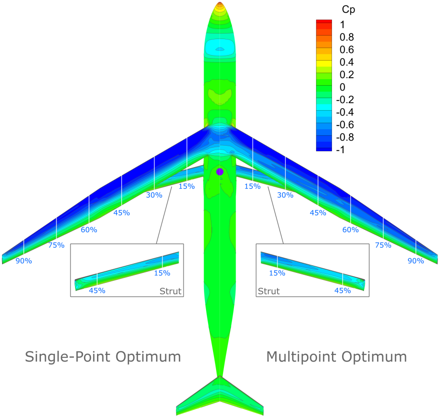
Design point 4: $M = 0.81$ (+0.03 nominal) and $C_L = 0.421$ (−10% nominal)

The optimizer adapts the wing design to improve off-design performance through a weakening of the shocks at those conditions.

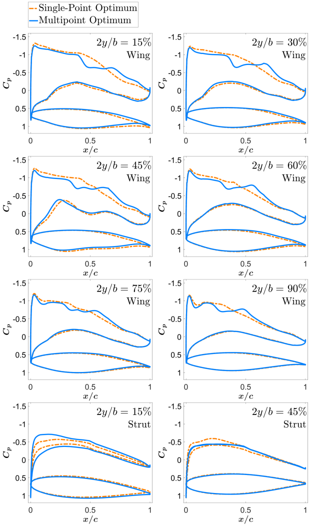
Results: Multipoint Optimized SBW100



Shock surfaces



Surface pressure contours



Pressure distributions

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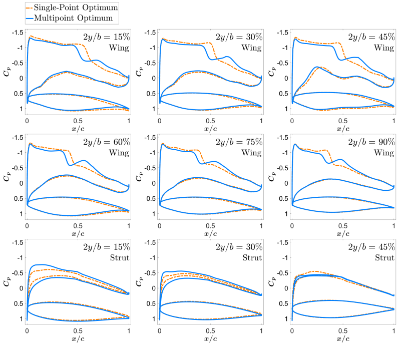
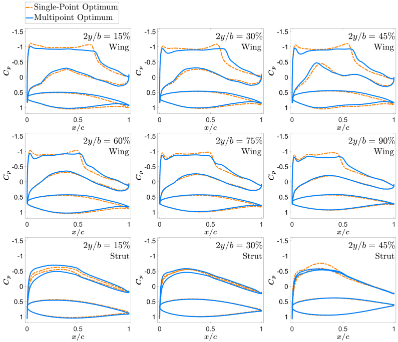
Results: SBW100 - Off-Design Performance



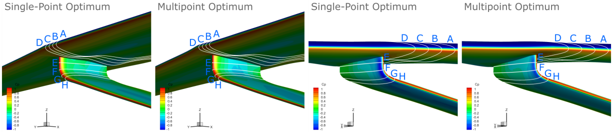
Design point 2: $M = 0.78$ and $C_L = 0.750$ (+10% nominal)



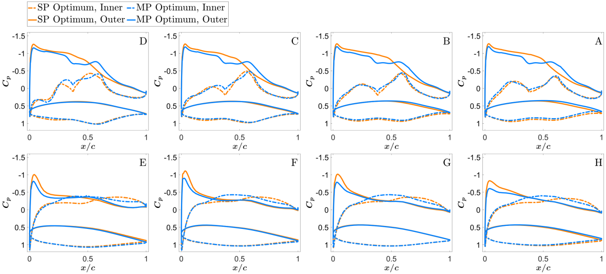
Design point 4: $M = 0.81$ (+0.03 nominal) and $C_L = 0.613$ (−10% nominal)

The optimizer adapts the wing design to improve off-design performance through a weakening of the shocks at those conditions. Strut lift also scales with the lift requirement.

Results: Multipoint Optimum Junction Design and Performance



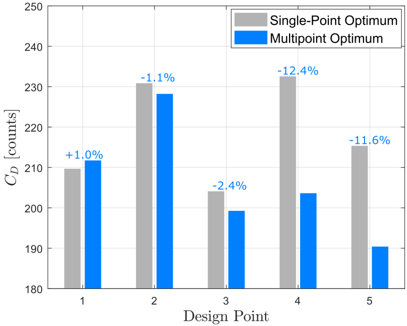
Inner (left) and outer (right) views of the wing-strut junction with surface pressure contours.



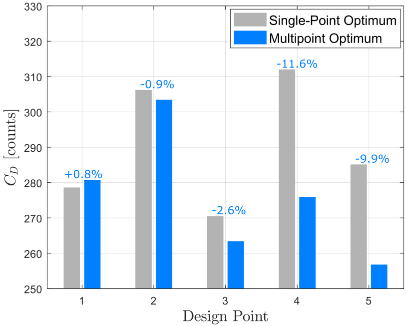
Airfoil profiles and pressure distributions over the wing and strut near the wing-strut junction.

The multipoint optimized junction design features are not very different from those of the single-point optimum.

Results: Off-Design Performance



CTW100



SBW100

Multipoint optimization only compromises drag by 2 counts at the on-design point, while improving off-design performance by up to 29 and 36 counts for the CTW100 and SBW100, respectively.

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Results: Multipoint Optimized Aircraft Performance

	Single-Point Optimum			*Multipoint Optimum*		
Parameter	CTW100	SBW100	Δ	CTW100	SBW100	Δ
Wing, Fuselage, Horizontal Tail (High Fidelity)						
Cruise L/D [–]	22.33	24.46	+9.5%	22.11	24.27	+9.8%
Cruise C_L [–]	0.468	0.682	+45.6%	0.468	0.682	+45.6%
Cruise C_D [–]	0.0210	0.0279	+32.9%	0.0212	0.0281	+32.6%
Cruise lift [lb]	101,720	97,000	−4.6%	101,720	97,000	−4.6%
Cruise drag [lb]	4,555	3,966	−12.9%	4,716	4,093	−13.2%
Full Aircraft (Low + High Fidelity)						
Cruise L/D [–]	18.96	21.40	+12.9%	18.80	21.26	+13.1%
Cruise C_L [–]	0.468	0.682	+45.6%	0.468	0.682	+45.6%
Cruise C_D [–]	0.0247	0.0318	+28.9%	0.0249	0.0321	+28.7%
Cruise lift [lb]	101,720	97,000	−4.6%	101,720	97,000	−4.6%
Cruise drag [lb]	5,365	4,532	−15.5%	5,411	4,563	−15.7%
Block fuel [lb]	5,028	4,643	−7.6%	5,050	4,657	−7.8%

[1] Performance parameters are for the 500 nmi nominal mission.

Conclusions and Future Work

Conclusions and Future Work

Conclusions

- Demonstrated the feasibility of designing a low-drag transonic strut-braced wing through *single-point* and *multipoint* aerodynamic shape optimization based on the RANS equations
- Mitigated shock formation and boundary-layer separation from the wing-strut junction at Mach 0.78
- With current technology levels, the optimized strut-braced-wing regional jet offers a 7.8% reduction in block fuel over a 500 nmi mission compared to a similarly-optimized E190-E2-like conventional tube-and-wing regional jet

Future Work

- Investigate the relative fuel burn savings of a strut-braced-wing single-aisle transport aircraft

Financial support and compute resources provided by:

CTW100: Conceptual Sizing Problem Definition

Objective (1):

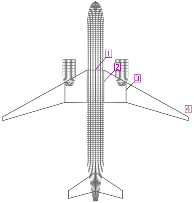
minimize Block fuel burn

Design variables (4):

w.r.t. Wing thickness-to-chord ratio (4)

Nonlinear constraints (1):

s.t. Min. fuel volume (1)



Thickness-to-chord ratio design variable locations

SBW100: Conceptual Sizing Problem Definition

Objective (1):

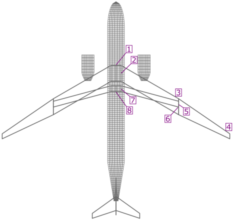
minimize Block fuel burn

Design variables (29):

w.r.t.
- Wing/strut chord (8)
- Wing/strut thick-to-chord ratio (8)
- Horizontal tail chord (2)
- Horizontal tail span (1)
- Horizontal tail x-location (1)
- Horizontal tail z-location (1)
- Vertical tail chord (2)
- Vertical tail span (1)
- Vertical tail x-location (1)
- Max. takeoff thrust (1)
- Initial cruise altitude (3)

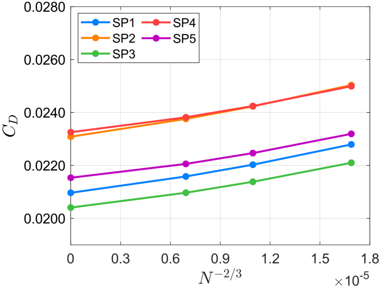
Nonlinear constraints (27):

s.t.
- Min. fuel volume (1)
- Max. wing loading (1)
- Min. thrust-to-weight ratio (1)
- Min. top-of-climb thrust (3)
- Min. static margin (2)
- Min. buckling margin (5)
- Min. buffet margin (12)
- Min. horiz. tail volume ratio (1)
- Min. vert. tail volume ratio (1)

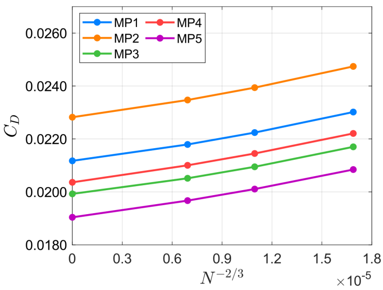


Thickness-to-chord ratio and Chord design variable locations

CTW100: Grid Convergence Studies



Single-point optimum.



Multipoint optimum.

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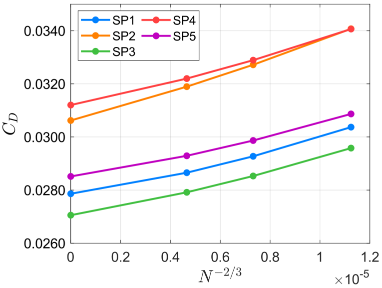
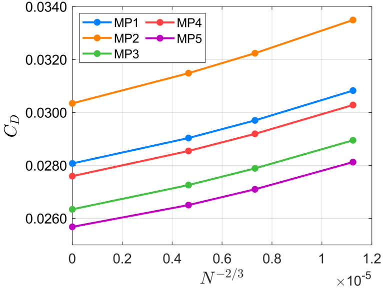
SBW100: Grid Convergence Studies



Single-point optimum.



Multipoint optimum.